REMARKS

This is a full and timely response to the outstanding final Office Action mailed July 23, 2003. Upon entry of the amendments in this response, claims 3 – 8, 10 – 12, 14, and 17 - 34 and remain pending. In particular, Applicant has amended claims 3, 10, 14, 17 19 and 21, has added claims 26 – 34 and has canceled claims 1 – 2, 15 and 16 without prejudice, waiver, or disclaimer. Applicant has canceled claims 1 – 2, 15 and 16 merely to reduce the number of disputed issues and to facilitate early allowance and issuance of other claims in the present application. Applicant reserves the right to pursue the subject matter of these canceled claims in a continuing application, if Applicant so chooses, and does not intend to dedicate the canceled subject matter to the public. Reconsideration and allowance of the application and presently pending claims are respectfully requested.

Indication of Allowable Subject Matter

The Office Action indicates that claims 6 and 7 would be allowable if rewritten in independent form, including all of the limitations of the base claim and any intervening claims. As set forth above, Applicant has amended claim 3 which serves as a base claim for both claims 6 and 7, and respectfully asserts that claims 6 and 7 are still in condition for allowance.

Rejections Under 35 U.S.C. §102

The Office Action indicates that claims 1 – 5, 8, 10 – 12, 14 – 18 and 21 stand rejected under 35 U.S.C. § 102(b) as being anticipated by *Abbott*. Additionally, the Office Action indicates that claims 1, 2, 10 – 12 and 14 – 20 stand rejected under 35 U.S.C. 102(e) as being anticipated by *Lee*. As set forth above, Applicant has canceled claims 1, 2, 15 and 16 and respectfully asserts that the rejection as to these claims has been rendered moot. With

respect to the remaining claims, Applicant respectfully traverses the rejection for at least the reasons set forth below.

With respect to the *Abbott* reference, Applicant respectfully asserts that *Abbott* does not teach or reasonably suggest a multi-layer interference filter as recited in Applicant's pending independent claims 3 and 21. Specifically, Abbott discloses the use of an etalon. Specifically, *Abbott* has used the term "etalon" in accordance with its common and ordinary meaning which defines an etalon as "a resonant optical cavity defined by two highly parallel substantially reflective surfaces." *Abbott*, column 1, lines 9 and 10.

Similarly, Applicant has used the term "multi-layer interference filter" in accordance with its common and ordinary meaning. Specifically, a multi-layer interference filter comprises multiple material layers that are stacked one on top of the other to form an interference filter. In this regard, Applicant conducted a brief Internet search for the term "multi-layer interference filter." Several examples of documents discovered during that search are attached hereto as exhibits A – C. Note that exhibit A, from "Optical Coatings Japan," describes multiple types of multi-layer interference filters that include the use of multi-layer films. Similar descriptions can be found in exhibit B to "Driel Instruments." The Examiner's attention is also respectfully referred to exhibit C to "Tech Focus," <u>which described both multi-layer interference filters and Fabry-Perot type interferometers. Of particular interest, the etalon of *Abbott* is a Fabry-Perot type interferometer, with the differences between multi-layer interference filters and Fabry-Perot type interferometers being described in exhibit C</u>.

Based on the foregoing, Applicant respectfully asserts that the filter component (10) of *Abbott* does not fairly constitute a "multi-layer interference filter" as recited in Applicant's claims. Therefore, for this reason alone, Applicant respectfully asserts that the rejections

under 35 U.S.C. §102 (b) to *Abbott* are improper. Applicant respectfully requests that the rejections based upon *Abbott* be removed.

Turning now the claims, independent claim 3 recites:

> 3. An optical system comprising:
> an optical filter having an optical filter component and a tuning assembly, said optical filter defining an optical path;
> ***said optical filter component being a multi-layer interference filter***, said optical filter component having a propagation axis, said optical filter component exhibiting a length of physical path along said optical path of said optical filter, said optical filter component being adapted to receive an optical signal such that, in response to the optical signal, said optical filter component propagates at least a first frequency of light;
> said tuning assembly engaging said optical filter component, said tuning assembly being adapted to alter said length of said physical path of said optical filter component along said propagation axis by selectively placing the optical filter component under one of axial tension and axial compression such that said optical filter component propagates at least a second frequency of light in response to the optical signal, the second frequency of light being different from the first frequency of light;
> wherein said tuning assembly includes a housing, said housing at least partially encasing said optical filter component;
> wherein said tuning assembly includes a retaining member adjustably engaging said housing; and
> ***wherein said optical filter component is arranged between said retaining member and at least a portion of said housing such that adjusting a position of said retaining member relative to said housing can change said length of said physical path of said filter component along said propagation axis.***
> (Emphasis Added)

Applicant respectfully asserts that the cited references are legally deficient for the purpose of anticipating claim 3, because at least the features emphasized above are not taught or otherwise disclosed in either of the references. Specifically, Applicant respectfully asserts that neither *Abbott* nor *Lee*, teaches or discloses at least the features/limitations of "said optical filter component being a multi-layer interference filter" in combination with "said optical filter component is arranged between said retaining member and at least a portion of said housing such that adjusting a position of said retaining member relative to said housing can change said length of said physical path of said filter component along said propagation

axis." Therefore, Applicant respectfully asserts that the rejection of claim is improper, and that claim 3 is in condition for allowance. Since claims 4 – 8, 10 – 12 and 14 incorporate all the features/limitations of claim 3, Applicant respectfully asserts that these claims also are in condition for allowance.

With respect to claim 21, that claim recites:

> 21. A method for tuning an optical filter, the optical filter defining an optical path and being adapted to propagate an optical signal along the optical path, said method comprising:
>
> providing an optical filter component having a propagation axis, ***said optical filter component being a multi-layer interference filter***;
>
> arranging the optical filter component along the optical path, the optical filter component exhibiting a length of physical path along the propagation axis, the optical filter component being adapted to receive the optical signal such that, in response to the optical signal, the optical filter component propagates at least a first frequency of light along the optical path; and
>
> ***altering the length of the physical path of the optical filter component along the propagation axis*** by selectively placing the optical filter component under one of axial tension and axial compression such that the optical filter component propagates at least a second frequency of light along the optical path in response to the optical signal, the second frequency of light being different from the first frequency of light; and
>
> ***tilting the filter component so that the propagation axis of the filter component and the optical path are not parallel.***
>
> (Emphasis Added).

Applicant respectfully asserts that the cited references are legally deficient for the purpose of anticipating claim 21, because at least the features/limitations emphasized above are not taught or otherwise disclosed in either of the references. Specifically, Applicant respectfully asserts that neither *Abbott* nor *Lee* teaches or otherwise discloses at least the features/limitations of "said optical filter component being a multi-layer interference filter," "altering the length of the physical path of the optical filter component along the propagation axis," and "tilting the filter component," as recited in claim 21. Therefore, Applicant respectfully asserts that claim 21 is in condition for allowance. Since dependent claims 17 –

20 incorporate all the features/limitations of claim 21, Applicant respectfully asserts that these claims also are in condition for allowance.

Newly Added Claims

Upon entry of amendments in this Response, Applicant has added claims 26 – 34. Applicant respectfully asserts that these claims are in condition for allowance because the recited features/limitations are not taught or reasonably suggested by the cited references, either individually or in combination. Therefore, the newly added claims are believed to be in condition for allowance.

Prior Art Made of Record

The prior art made of record has been considered, but is not believed to affect the patentability of the presently pending claims.

CONCLUSION

In light of the foregoing amendments and for at least the reasons set forth above, Applicant respectfully submits that all objections and/or rejections have been traversed, rendered moot, and/or accommodated, and that the now pending claims 3 – 8, 10 – 12, 14, and 17 - 34 are in condition for allowance. Favorable reconsideration and allowance of the present application and all pending claims are hereby courteously requested. If, in the opinion of the Examiner, a telephonic conference would expedite the examination of this matter, the Examiner is invited to call the undersigned attorney at (770) 933-9500.

Respectfully submitted,

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I hereby certify that this correspondence is being deposited with the United States Postal Service as first class mail, postage prepaid, in an envelope addressed to: Assistant Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450, on

10/03/03.

Stephanie Bailey
Signature

Optical Coatings Japan

Interference Filters

The filters exploit the interference effect to transmit or reflect desired wavelength regions. Compared with absorptive colored glass filters and gelatin filters, interference filters have extremely good contrast, with very narrow or sharply defined transmission bands. Although most interference filters have transmission side bands on both sides of the center wavelength, these bands can be blocked by combination with a multi-layer blocking filter or glass filter. Due to the above properties, the filters are being applied to the optical instruments such as calorimeters, flame spectrometers, monochromators, and optical systems such as laser systems, space systems, optical communication systems, and optical data storage systems in the fields of physics, chemistry, biology, medicine, pharmacology, and astronomy

Characterization of Interference Filters

Effect of the Angle of Incidence

When a filter is tilted with respect to the incident light, its transmission band shifts toward the shorter wavelength. At angles up to about 20°, the shape of the spectral characteristic remains approximately the same, but at larger angles of incidence, the transmission band splits into two separate peaks, because the P-component (parallel to the plane of incidence) and the S-component (perpendicular to the plane of incidence) are shifted by different amounts. In an M I F-S filter, the peak of the S-component is shifted more than that of the P-component as shown in Fig. 3. The shifts also depend slightly on the wavelength. Since the sharpness of the transmittance curve of P-component is virtually independent of the inclination, this angular dependence can be turned to advantage: a single interference filter can be tilted at various angles to obtain a variety of wavelengths of monochromatic light. However, in this case, a polarizer should be used at the same time so as to utilize only P-polarization. In normal usage, angles of incidence greater than 20° are not recommended.

Ambient Temperature

Except for special types, interference filters can be used for long periods at temperatures up to 50°C and for short periods at temperatures up to about 80°C.

Metal-Dielectric Interf r nce Filters MIF-S type

A metal interference filter has a triple-layer structure consisting of two partially transmitting metal layers separated by a transparent dielectric layer. These layers are deposited on a glass or quartz substrate. For protection, a glass, quartz, or colored glass filter is cemented onto it. The optical path length between the two metal layers is 1/ 2 of the transmitted wavelength, or an integer multiple of 1/2 of the wavelength. Other wavelengths are almost entirely blocked. The filter is called a first-order, second-order, or third-order filter depending on whether the optical path length is equal to the half-wavelength, twice the half-wavelength, or three times the half-wavelength. For filters of equal peak transmittance, the higher the order, the narrower the half-width is and the better the characteristic is. High-order filters have the disadvantage, however, that the lower-order transmission side band on the long-wavelength side and the high-order transmission side band on the short-wavelength side approach the main transmission band. Except for special requirement, first- and second-order filters are available. For instance, a 656nm second-order interference filter has a third-order transmission band in the vicinity of 437nm (2/ 3 X 656), and a first-order transmission band in the vicinity of 1.3µm (2 X 656) in the infrared. While for interference f-filters of below 959nm, the second- order interference is utilized, for those of above 960nm, the first-order interference is utilized, and the higher-order side bands are completely blocked by glass filters for both cases.

Typical spectral characteristics

Metal-Dielectric Interference Filters MIF-W type

A W-type filter is narrowband filter with a sharply sloped transmittance curve. It has a five-layer configuration equivalent to two S-type filters, stacked one atop the other. Although it has a wider half-width than that of an S-type filter, its contrast Is also better by a factor of 20, due to the steep slopes of its transmittance curve. When a flame spectrometer is used in atomic spectroscopy of sodium (589nm), calcium (622nm) and potassium (768nm), for example, if an S-type interference filter is employed, the closeness of the sodium and calcium lines complicates the measurement, and background effects appear. With a W-type interference filter, there are almost no interfering effects among the Na, Ca, and K lines, so sufficient sensitivity and accuracy can be obtained. W-type filters are also used to separate the 546nm and 578nm lines, or the 405nm and 436nm lines, in mercury spectral lines.

Typical spectral characteristics

All-Dielectric Interference Filters DIF-type A/B/C

This filter consists of dielectric multilayer films instead of metal films of MI F-S interference filter. This filter is

also called single-cavity filter, and has a narrow half-width and high maximum transmittance. All-dielectric filters are classified' as type A, B, or C depending on the ratio of the half-width to the center wavelength. Narrowband interference filters of these types show different measured values of maximum transmittance and half-width depending on the wavelength purity of the spectrophotometer. If the effective bandwidth of the spectrophotometer is 1/5 the half-width of the interference filter or less, however, the measured values are constant.

Typical spectral characteristics

Short Pass Filter

This filter has the following features: minimization PDL for transmission and reflection; high isolation by a steep slope, high durability by OCJ's proprietary Plasma Ion Deposition process. Custom design is available.

Typical characteristics:

T 1.48µm </=0.3dB R 1.55µm >/=30dB

Typical spectral characteristics

Long Pass Filter

This filter features high durability by OCJ's proprietary Plasma Ion Deposition process. Custom design is available.

Typical characteristics:

T 1.55µm </=0.3dB R 1.31µm >/=30dB

Typical spectral characteristics

All-Dielectric Interference Filters DIF-BPF

A band-pass filter with a rectangular band characteristics consists of dielectric multilayer films instead of metal films of MIF-W interference filter. The number of cavities can also be increased to create a multi-cavity filter. Band- pass filters are classified as type BPF-1 to BPF-5 according to the ratio of the half bandwidth to the center wavelength.

Typical spectral characteristics

Infrared Interference Filters IR-BPF

An infrared band-pass filter is fabricated by depositing multilayer films on a suitable substrate, such as quartz, sapphire or germanium. These filters are classified as IR-BPF-1 to IR-BPF-4 according to the ratio of the half-width to the center wavelength. This type of filter has a number of transmission side bands on both sides of the center wavelength, but they can be removed by various blocking filters, or by exploiting the absorption of the

substrate.

Typical spectral characteristics

Infrared Interference Filters IR-LPF

This interference filter is a long-wave-pass filter with a sharp cutoff at a specific wavelength.

Typical spectral characteristics

Cold Filters

The cold filter has the opposite spectral characteristics of a cold mirror: it transmits visible light and reflects infrared light. Two types are available, with different substrate materials: CF-A and CF-B.
CF-A type : This type has an average transmittance of 85% or above in the visible region and a reflectance of 85% or above at 1 um, so it is useful with halogen and xenon lamps which have high spectral energy in that vicinity. The coating can also be applied directly to the condenser lens to make it function as a cold filter.
CF-B type : This filter utilizes a beat absorption glass plate as a substrate. Combining spectral characteristics of the substrate with that of A type, this filter has an beat proof effect in a longer wavelength range.

Typical spectral characteristics

Dichroic Filters

A dichroic filter has spectral characteristics similar to a dichroic mirror, but is used for normal incidence, whereas a dichroic mirror is used for non-normal incidence. Standard dichroic filters are available as Yellow, Magenta, Cyan, Blue, Green and Red filter types.

Typical spectral characteristics

Neutral Density Filters

These filters have nearly constant spectral transmittance in a specified wavelength range. Neutrality is excellent, but a constant absorption is present across the entire bandwidth, due to the absorbing material deposited. These filters are used mainly as attenuation filters.

Near-Infrared Blocking Filters NIC

These filters which reflect NIR light and correct colours of the visible light are essential optical components for colour TV camera tubes. The filter coating can be applied directly to the lens of the window of the camera tube.

Typical spectral characteristics

Colour Conversion Filters

The filters are for the conversion of the colour temperature of light sources.

Relative Luminosity Filters

Special characteristics of this filter closely follow the relative luminosity curve.

ENVIRONMENTAL FACTORS

Temperature

Most Oriel Band Pass Interference Filters are designed to operate from -50°C to +80°C; they may be operated intermittently to 100°C. The rate of temperature change should not exceed 10°C/minute. At 120°C or above, permanent changes and possible destruction can occur.

Apart from irreversible changes at high temperatures, the most noticeable temperature effect is the variation of central wavelength. At increased temperature, the central wavelength increases. This wavelength change is almost linear between -60°C and +60°C with values between 0.01 and 0.03 nm/°C; above 120°C, the change in central wavelength may be irreversible. There are also very slight changes in bandwidth (about 0.001 nm/°C) and peak transmittance (about 0.01%T/°C) with increasing temperature.

Humidity

All Oriel ultraviolet and near infrared Band Pass Interference Filters are edge sealed as a barrier to environmental moisture. We test our filters to MIL-STD-810C method 507, procedure 1. This test consists of placing the filter in an environmental test chamber and cycling the temperature and humidity over a 24 hour period. Each 24 hour time period is termed a cycle, and the number of cycles to which it is tested, is specified for each filter type. After the completion of the test, the filter is inspected for spectral performance and physical damage.

Other Oriel multi-layer filter products such as long and short pass filters comply with the slightly less stringent MIL-C-675A (para. 4, 6 and 9) Temperature and Humidity Specification. This test consists of placing the test sample in an environmental chamber for 24 hours at 95% relative humidity and at 50°C. Then the filter is inspected for spectral performance and physical damage.

Some infrared interference filters have extremely hard and durable coatings. These coatings are unaffected by ambient humidity and are left exposed to the atmosphere. These coatings also meet the requirements of MIL-STD-810C method 507, procedure 1.

Filter Orientation

Most band pass interference filters are constructed using some type of auxiliary absorptive blocking filters. Each side of the filter has a distinctively different appearance. One side will be highly mirrored while the other side will be colored (opaque or anywhere from deep violet to deep red).

Always orient the band pass filter so the highly mirrored side is facing the source of radiation. Most of the rejected radiation is reflected and does not heat the internal components of the filter.

Angle of Incidence

Filter specifications are usually given for collimated radiation incident normal to the filter surface. In many applications, collimated, normal incidence radiation is not practical or even possible. You can, however, estimate the results of using off-normal incident radiation.

Band pass interference filters are composed of a series of layers of precisely controlled thicknesses of dielectrics and metals. Changing the angle of incidence increases the apparent thickness of these layers. However, the phase difference between the interfering waves decreases as angle increases. The effects of off-normal radiation are three fold; there is a decrease in the central wavelength; the transmittance decreases and the bandwidth increases; for off-normal angles less than °25, the effect on transmittance and bandwidth are minimal. The shift in central wavelength with angle of incidence can be used to precisely "tune" a narrow band filter.

The decrease in central wavelength is a function of the refractive indices of the deposited films and the angle of incidence. The effective refractive index, n*, of the filter, is used to simplify the relational formula. For collimated radiation incident at angle θ, where θ< 25:

$$\lambda_\theta = \lambda_0 [1 - (n_0/n^*)^2 \sin^2 \theta]^{1/2} \quad \text{............(6)}$$

Where:

λ_θ = Central wavelength at angle of incidence θ

λ_0 = Central wavelength at normal incidence (θ = 0)

n_0 = Refractive index of the medium surrounding the filter

n^* = Effective refractive index for the filter

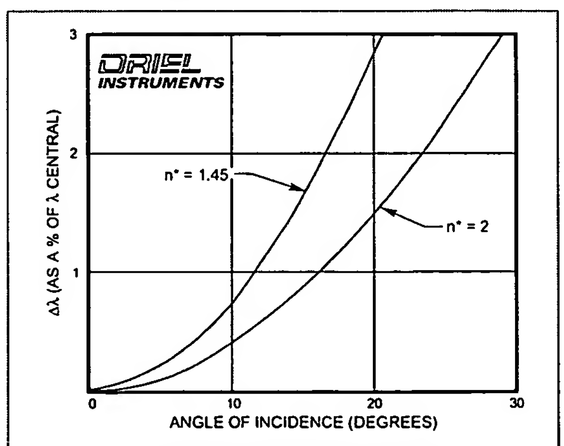

Fig. 9 Approximate wavelength shift with angle of incidence for the n* values of our interference filters.

For typical visible and near infrared band pass interference filters (400 - 1100 nm), the experimental values of n* have been found to be 2.0 for high index spacer layers, and 1.45 for low index spacer layers.

When the angle of incidence is large, > 30°, the spectral pass band characteristics of the filter can be so degraded as to yield two distinct peaks and transmittance becomes dependent on polarization.

Table 3 lists multiplying factors for off-normal collimated incident radiation. To find the new central wavelength at an off-normal angle, simply multiply the wavelength at normal incidence by the appropriate factor for that angle.

Table 3 Multiplying Factors for Off-normal Collimated Light

Angle (degrees)	High Index Spacer Layer (n* = 2)	Low Index Spacer Layer (n* = 1.45)
0.25	1.0	1.0
0.5	1.0	1.0
1.0	1.0	0.9999
2.0	0.9999	0.9997
3.0	0.9997	0.9994
4.0	0.9994	0.9998
5.0	0.9991	0.9982
7.5	0.9979	0.9959
10.0	0.9962	0.9928
15.0	0.9916	0.9839
20.0	0.9853	0.9718
25.0	0.9774	0.9566
30.0	0.9683	0.9387

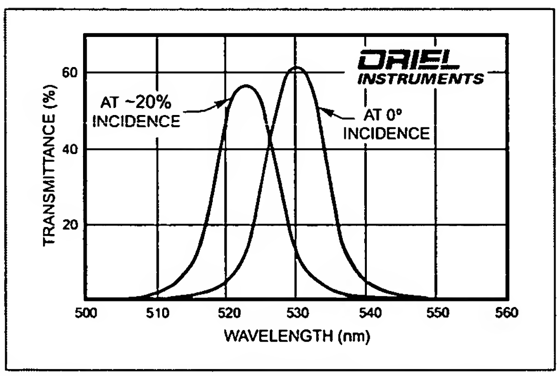

Fig. 10 530 nm center wavelength filter at normal incidence and at ~20°.

Divergent or Convergent Incident Radiation

A diverging or converging beam incident on a filter means a spread of incident angles. The result is a broadening of the apparent band pass and a shift to lower wavelengths. Since the transmittance is angle dependent, the beam which passes the filter will have a slight angular wavelength dependence.

The change in center wavelength can be obtained by using the half cone angle in equation (6), on the previous page.

For solid cone angles to 20°, the change will be about half of that calculated. Band pass interference filters with bandwidths of less than 3.0 nm have negligible center wavelength changes with convergent or divergent beams with up to 5° full cone angle (F/11).

FILTERS AND MONOCHROMATORS

A Monochromator or an Interference Filter?

For maximum throughput efficiency with a monochromator, the F/# of the input optics must match that of the monochromator. This puts a fundamental limit on the demagnification of a source to try to get as much light as possible through the slit. An interference filter, on the other hand, has a large acceptance aperture and can have transmission in the range of 50 - 60%. With extended (large) sources, an interference filter can have up to 500 times greater throughput than a monochromator.

A Monochromator Used With an Interference Filter

Interference filters are effective in reducing the stray light accompanying the output from a fixed wavelength grating monochromator. If a high intensity continuous source is used, the filter should be placed between the exit slit and the detector to reduce the thermal load on the filter.

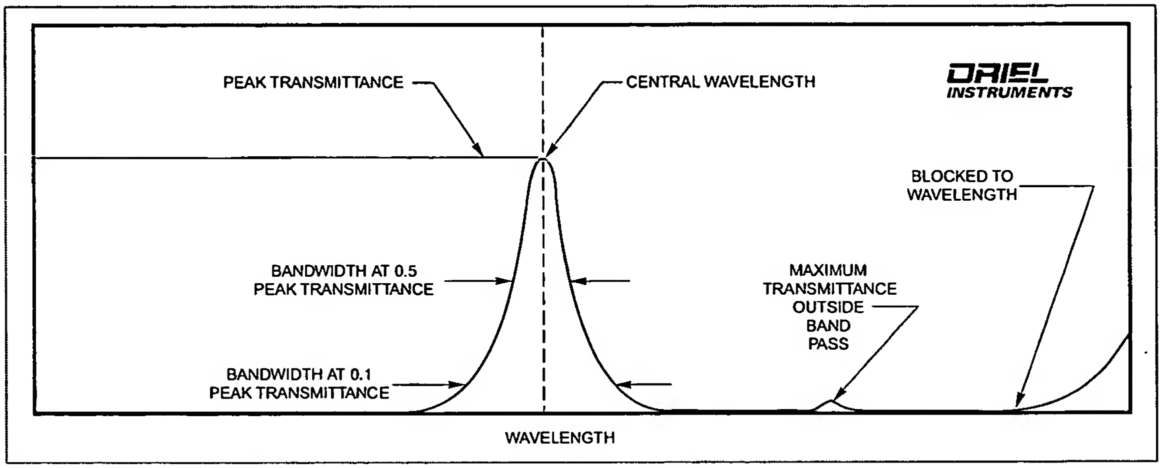

Fig. 11 Typical Interference Filter.

INTERFERENCE FILTER TRANSMISSION/ REJECTION

With an interference filter, it is very common to think of the ratio of peak transmission to blocking as a system signal to noise ratio. This assumption can lead to very serious errors. In order to obtain a true system signal to noise ratio, the spectral power distribution of the source and response of the detector must be considered as well as the peak transmission, bandwidth, band shape and blocking of the interference filter.

For example, consider the use of an interference filter with a central wavelength of 400 nm, a bandwidth of 10 nm, a peak transmission of 40% and blocking of 0.01% from X-ray to the far infrared in a system which has a tungsten light source and a silicon photodetector. With a typical tungsten source, the intensity in the 1000 nm region can be up to 100 times that at 400 nm. Additionally, the silicon photodetector can have 3 to 5 times as much response in the 800 to 1000 nm region as at 400 nm. If the combination of interference filter, light source and detector described above were to be used in a 400 nm absorbance photometer, the result would probably be misleading.

To obtain a good indication of the real signal to noise ratio in such a system, make a signal measurement with the 400 nm interference filter, light source and detector in place. Then place a sharp cut-on colored glass filter in series with the interference filter and take a measurement. The colored glass filter will absorb the signal at 400 nm leaving most of the "noise" component.

A simple way to improve a system signal to noise ratio is to use two filters in series. The second filter could be a colored glass to eliminate most of the visible and near infrared, or the same type of interference filter.

A near worst case measurement with 53810 Filters (10 nm bandpass at 420 nm), a tungsten halogen source (3200 K) and a silicon detector gave the results below. A 470 nm long pass filter was used to block all the light coming through the filter bandpass to record the leakage signal.

	Relative Signals	
	Single Filter	Two Filters
250 - 1100* nm	100	47.5
Leakage Signal above 480 nm	3×10^{-5}	$<1 \times 10^{-8}$

* Most of this signal is in the 400 - 440 nm transmitting region of the filter.

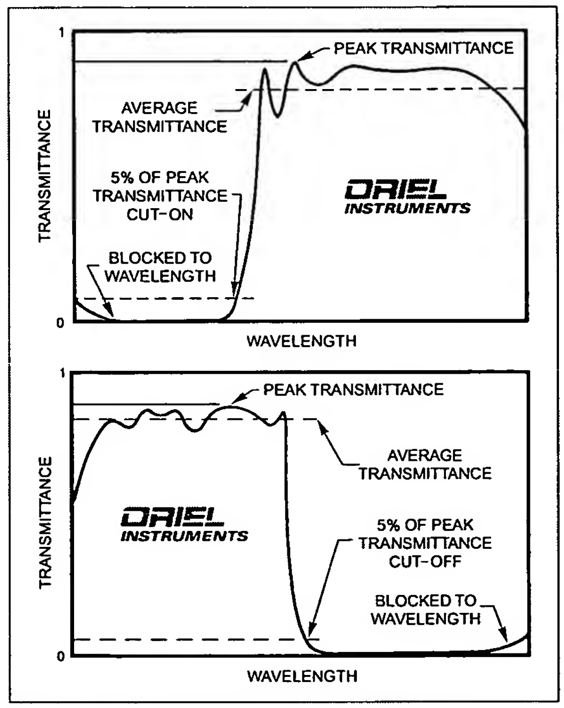

Fig. 12 Typical Long Pass (top) and Short Pass (bottom) Filters.

Optical Interference Filters

Interference filters provide a promising tool for channel dropping and tuning laser wavelength.

By Nicolae Miron, Optune Technologies Inc.

"Why should I choose an interference filter instead of an absorption filter or a grating for WDM applications?" This question, which has become quite common among industry professionals, is easily answered. Because interference filters provide interference between multiple beams, they offer superior performance in WDM applications, including low insertion loss, high rejection ratio, steep slopes, and tunability. Additionally, interference filters can work in either transmission or reflection modes, realizing either band pass or band reject functions. They are also available as either fixed wavelength filters (constant band pass and reject bands) or as tunable filters where the band pass and reject band can be positioned within a certain wavelength range.

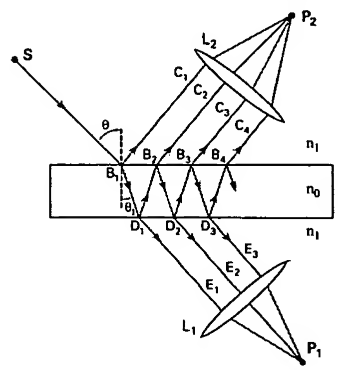

Figure 1: Interference between multiple beams generated by transmission at point P1, and at reflection in point P2

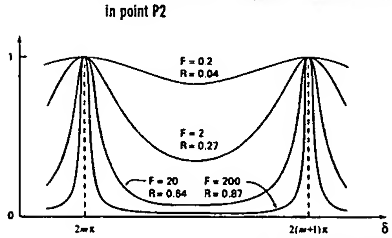

Figure 2: Multiple beam fringes of equal intensity in transmission [1]. The order of the longitudinal mode of the interferometer is expressed by integer m.

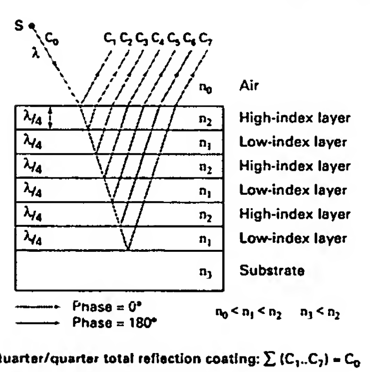

Figure 3: Multi layer total reflective coating [2].

Multiple Beam Interference Filters

Before we delve into the details, a brief explanation of the operating principle surrounding interference filters is required. Figure 1 summarizes the interference of multiple beams generated by reflection and transmission. A glass plate with refractive index n_1, thickness *h* and surrounded by air with refractive index n_0 has partially reflective layers on its top and bottom faces. A collimated monochromatic beam with wavelength λ, generated by the light source *S*, is incident in point B1 on the top reflective layer at an angle of incidence θ. After going through the top reflection layer with reflectivity r_1, the beam is propagating inside the glass with angle θ_1 to the normal at B1. After multiple reflections inside the glass, the beams C1, C2, C3, ... are generated on the same side of the glass plate as the incident beam, and the beams E1, E2, E3, ... are generated on the side opposite to the incident beam. Usually, C1, C2, C3, ... are called *reflection* beams, and the E1, E2, E3, ... beams that travel through the bottom reflective layer with reflectivity r_2 are called *transmission* beams. The lens L1 collects the beams E1, E2, E3, ... into the point P1, where all transmission beams interfere. Similarly, the lens L2 collects all reflected beams into the point P2, where they interfere. The phase shift δ between two neighboring beams is [1]:

$$\delta(\lambda, n_1, h, \theta_1) = \frac{4\pi}{\lambda} \times n_1 \times h \times \cos\theta_1 \quad (1)$$

Relative intensity I_R in P2 (or transfer function for reflection) given by the interference between p reflected beams (when $p \rightarrow \infty$ is expressed as [1]:

$$I_R(\delta) = \frac{4 \times R \times \sin^2 \frac{\delta}{2}}{(1-R)^2 + 4 \times R \times \sin^2 \frac{\delta}{2}} \quad (2)$$

Where: $R = r_1 \times r$

Relative intensity I_T at P1 (or transfer function for transmission) given by the interference between p transmitted beams (when $p \rightarrow \infty$), is expressed as [1]:

$$I_T(\delta) = \frac{T^2}{(1-R)^2 + 4 + R \times \sin^2 \frac{\delta}{2}} \quad (3)$$

Equations (2) and (3) are similar and express the fact that the transmission of the interferometer depends on the wavelength λ, the refractive index n_1 of the media where the multiple beams are generated (specifically glass), the distance h between the reflective layers, and the angle of incidence. The graph showing the dependence of $I_T(\delta)$ for different number p of interfering beams is shown in Figure 2, where the parameter F is defined as [1]:

$$F = \frac{4 \times R}{(1-R)^2} \quad (4)$$

It is a very common practice in interferometry to use the parameter finesse F, which is defined as the ratio of the separation between the peaks and the *full width at half maximum (FWHM)* of the peaks. The relationship between finesse F and reflectivity R is [1]:

$$F = \frac{\pi \times \sqrt{R}}{1-R} \quad (5)$$

Filter selectivity depends largely upon the *number of interfering beams* (Figure 2); more beams give better selectivity and vice-versa. Interference filters can have a large number of interfering beams and this feature is one of the advantages that interference filters have over other types of filters. Furthermore, the selectivity can be adjusted simply by clipping the output beams, which can eventually increase the insertion loss of the filter.
The transmission (and reflection) depends periodically on the elementary phase shift δ. This phase shift depends upon the wavelength, refractive index, gap between the reflective layers and angle of incidence, as expressed by the equation (1). These dependencies will be discussed later.

Multilayer Interference Filters

Interference filters usually consist of multiple dielectric layers with very low absorption. Each layer has an optical function similar to the glass plate

shown in Figure 1. All of the layers have the same thickness, but are made of different dielectric materials that introduce a controllable phase shift of the transmitted beam and also of the reflected beams. These stacked layers can perform different optical functions such as total reflection (see Figure 3) or minimum reflection (anti-reflective).

Multiple layers are cascaded in stacks to achieve a simple function such as reflection with a certain reflectivity. Two dielectric stacks denoted *Stack 1* and *Stack 2* (see Figure 4) could contain a gap between them, thus forming an interferometer similar to that shown in Figure 1, but with the gap consisting of air instead of glass. The transmission characteristic of such an interferometer is shown in Figure 2. Inherently, the transfer function of a simple interferometer has multiple peaks, each of them with a Lorentzian-like shape on top and a certain slope. Most optical filtering applications require characteristics that are only achievable by optically cascading interferometers.

By cascading multiple stacks of multi layer coatings as illustrated in Figure 4, filters with flattop characteristics and very sharp edges can be achieved. This is critical for WDM applications where effective channel rejection is required.

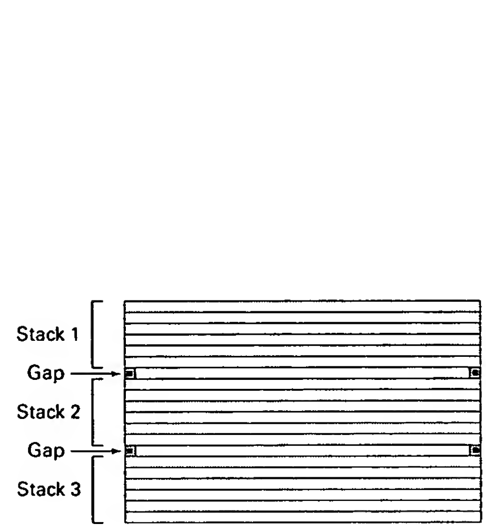

Figure 4: Optical cascade of multi layer dielectric stacks with gaps [2]

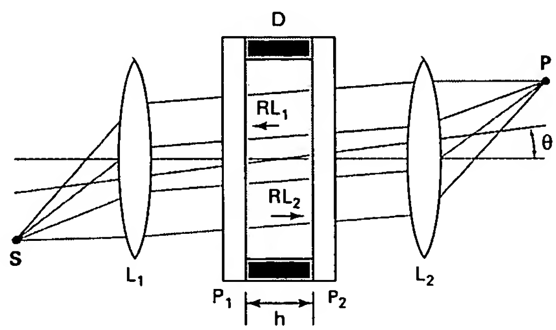

Figure 5: Simple Fabry-Perot Interferometer

Fabry-Perot Type Interferometers

A Fabry-Perot interferometer consists of two parallel glass plates P1 and P2 with reflective layers RL1 and RL2 spaced by a gap h (shown schematically in Figure 5).

A Fabry-Perot interferometer also has multiple interfering beams similar to the optical setup shown in Figure 1, but with some important differences:

- The angle of incidence θ is very small ($\theta \approx 0$)
- Reflectivities r1 and r2 of the layers RL1 and RL2 are high (> 0.9)
- Gap h between the reflective layers RL1 and RL2 is air or it can be filled with an electro-optic material such as a liquid crystal or electro-optic crystal, in order to control its refractive index n_i by electrical means.
- Reflective layers RL1 and RL2 (plane or spherical) create a resonant cavity that defines the wavelength selective properties of the interferometer.
- The number of interfering beams is very large, limited only by the reflectivities r_1 and r_2.

Properties of Interference Filters

The transmission characteristic of any interference filter depends periodically upon the elementary phase shift δ, which also depends upon:

- *Wavelength* λ. If all the other parameters (such as the angle of incidence θ, refractive index n_i and the spacing between the reflective layers h) are constant, the transmission peaks of the filter will have very well defined and stable values. These can be used as wavelength references in etalons.
- *The refractive index* n_i of the optical medium between the reflective layers. This dependence can make the interference filters tunable by simply changing the refractive index n_i. The easiest way to accomplish this is by using the electro-optic effect, which may also change the polarization states of the interfering beams, decreasing filter rejection. In the early 1990s, there were attempts to build tunable optical filters by changing the refractive index of a liquid crystal that filled the gap between the reflective layers. However, this methodology failed to produce a functional unit.
- *The gap size h* between the reflective layers. By changing h by very small values, the filter can be tuned into a certain wavelength range without affecting the polarization state of the interfering beams while keeping the same width of the peaks. This approach is extensively used in tunable band pass Fabry-Perot filters built mainly with MEMS. Tuning of such a filter is limited to the same longitudinal mode m of the cavity. Also, in this case the insertion loss of the filter is modulated with the amplitude distribution of the mode, which is a limiting factor in tunable optical filters made with Fabry-Perot interferometers.

On the other hand, wavelength etalons must keep the gap h constant with maximum accuracy to achieve good wavelength stability. Spacing h is the most difficult parameter to keep constant, mainly due to changes in temperature.

- *The angle of incidence* θ. Any change in the angle of incidence shifts the wavelengths of the transmission peaks. Peak widths are also shifted because the receiving optics clip the output beams to a certain extent. This tuning approach is used in some types of tunable band pass optical filters with a rotating glass plate covered with parallel reflective coatings. These filters are relatively new entrants to the market.

1. M. Born, E. Wolf, Principles of Optics, Cambridge University Press, 7-th edition, § 7.6.1, p. 360.
2. Melles Griot 1999 Catalog, Chapter 5.

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